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Research paper

Assessment of potato response to climate change and adaptation strategies

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ABSTRACT

This study was conducted to simulate the climate change impacts on potato production and evaluate the planting date and variety management as possible climate change adaptation strategies in Isfahan province, Iran. Two types of General Circulation Models (HadCM3 and IPCM4) and three scenarios (A1B, A2 and B1) were employed. Daily climatic parameters were generated by Long Ashton Research Station-Weather Generator (LARS − WG). The SUBSTOR-Potato model was used to simulate the baseline and future potato growth and development. Results indicated that LARS-WG and SUBSTOR-Potato had an appropriate accuracy to simulate climatic and growth parameters of potato. Simulated results showed that the maximum leaf area index (LAI), days to tuber initiation (DTTI), days to harvest (DTH) and fresh tuber yield of evaluated variety will be declined as affected by future climate change. Based on the simulation results, delayed planting date (31 May) would increase tuber yield under future climatic conditions. In the contrary, early planting (30 April) would accelerate harmful effects of climate change on potato yield. The medium and early maturing varieties showed a better tuber yield under climate change conditions than common (delayed maturing) variety. In essence, early maturing variety and delayed planting date are reported as the most efficient agronomical approaches for mitigating harmful effects of climate change and proposed to be considered in designing and managing potato ecosystems of the region for future climatic conditions. Generally, our results highlight the importance of considering early maturing variety and delayed planting date as the efficient agronomical approaches for mitigating harmful effects of climate change on potato production.

1. Introduction

Total field crops production in Iran is estimated at about 94 million tons on 13,500,000 ha in 2013. Potato (*Solanum tuberosum* L.) is one of the important crops grown in Iran. It is grown almost all over the country under varied soil and climatic conditions. Total potato production area is approximately 191,000 ha with total production of 4.05 million tons in 2013 (MAJ, 2014).

The historic trend of mean annual temperature of Iran indicates an increase of 0.05 °C per year (Moradi et al., 2013). Based on this fact, it is expected that the emissions of greenhouse gases will continue and as it has been seen in the recent years in scientific experiments and real conditions, combined effects of these two parameters will cause some predictable and unpredictable climatic changes (IPCC, 2007). This environmental change will consequently have serious impacts on growth and development of different processes. For example, elevation of temperature could affect physiological processes such as photosynthesis, respiration and partitioning of photoassimilate (Chartzoulakis and Psarras, 2005; Yang and Zhang, 2006). The final effect of climatic change will depend on local conditions. So, in regions with cold spring and summer seasons that the growing season length is limited, warmer conditions might be beneficial for crop yields. But, locations with warmer climate will see yield reductions if temperature increase (Meza et al., 2008). Increasing temperature can lead to shorten growth and grain-filling duration of crops (Boote, 2011). Additionally, various cultivars of crops may show different responses to future climate changes due to different lengths of seasons.

The negative impacts of climate change on potato productivity have been extensively reported in the literature (Rosenzweig et al., 1996; Hijmans, 2003; Holden et al., 2003; Daccache et al., 2011; Van der Waals et al., 2013; Sparks et al., 2014; Kumar et al., 2015). Although, farmers are not able to change or manage the climatic conditions but

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some factors such as soil, water, cultivars type and agricultural practices can be managed to reduce the adverse impacts of climate change (Ozkan and Akcaoz, 2002; Moradi et al., 2013). Adaptation is a known way for reducing the negative impacts of climate change on crop productions (Moradi et al., 2014). The aim of adaptation is minimizing the potential negative impacts of climate change while maximizing opportunities for adjustment (Rosenzweig and Tubiello, 2007; Moradi et al., 2013). In IPCC (2007) reports, various adaptation strategies for moderating the projected climatic changes including changing planting date, altered crop rotations, changing cultivars, more efficient water use; altering the timing or location of cropping activities; development of new agricultural areas, improving the effectiveness of pest, disease and weed management practices were suggested. Without adaptation and mitigation strategies, climate change is generally problematic for agricultural production and economies (Smit and Skinner, 2002).

The crop models such as SUBSTOR-Potato can be used for crop growth and development estimating in climate change conditions. The model has been used previously for potato and climate change impact assessments (Han et al., 1995; Travasso et al., 1996; Hodges 1998; Holden et al., 2003; Stastna et al., 2010; Daccache et al., 2011 ; Arora et al., 2013; Martre et al., 2017; Raymundo et al., 2017).

The present study was undertaken with the aims of quantifying the potential impacts of climate change on phenology, growth and tuber yield of potato and to evaluate the effectiveness of planting date and variety management strategies for minimizing climate change impact on potato production in Iran. To achieve these objects, the experiment was performed during 2011, 2012 and 2013 growing seasons in Fereydoon-Shar region, Isfahan province, Iran.

2. Material and methods

2.1. Study area

The study was conducted in Fereydoon-Shahr region, Isfahan province, Iran. The province is located in the center of Iran, within 30° 43′ and 34° 27′ north latitude and 49° 36′ and 55°31′ east longitude and covers an area of about 107,027 Km^2. This area is inhabited by more than 5 million people and agriculture plays the main economic role. Fereydoon-Shahr region with minimum temperature −17.6 °C, maximum temperature 34.6 °C, cumulative annual radiation 7781 MJ m^{-2} and annual precipitation 600 mm, has a suitable condition for potato growth and cultivation. Cultivated area of the region including field and horticultural crops is 440,743 ha (MAJ, 2014). Potato is grown during spring-summer season (May to October) under irrigated conditions with a fairly intensive use of chemical fertilizers. Minimum temperature, maximum temperature, cumulative annual radiation and annual precipitation of the region during the potato growing season (May to October) were 3.6 °C, 34.6 °C, 4076 MJ m^{-2} and 34.8 mm, respectively.

2.2. Data set and climate model

We used climate projections from the Hadley Centre Coupled Model version 3 (HadCM3) and France and Institute Pierre Simon Laplace (IPCM4), United Kingdom. The HadCM3 model is a coupled atmosphere-ocean global circulation model (GCM) developed at the Hadley Centre has stable control climatology and does not use flux adjustment (Meza et al., 2008). The scenarios used were SRES (Special Report on Emissions Scenarios) − A2, SRES − B1 and SRES − A1B. The SRES − A2 indicated very heterogeneous world conditions with high population growth rate, slight economic development and slow technological change (IPCC, 2000; Prudhomme et al., 2010). The SRES − B1 defines a convergent world with a global population that peaks in mid-century and rapid changes in economic structures towards a service and information economy with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity but without additional climate initiatives (Prudhomme et al., 2010; Wetterhall et al., 2009) and the SRES − A1 B scenario describes a world of rapid economic growth, a global population that peaks in mid-century and declines thereafter, and more efficient technologies based on a balanced energy mix (IPCC, 2000).

Daily climate data including solar radiation (Mj m^{-2} day^{-1}), maximum and minimum air temperature (°C) and precipitation (mm) were obtained for the period of 1982–2012 for Fereydoon-Shahr meteorological station.

LARS − WG (Long Ashton Research Station-Weather Generator) was used to generate daily climatic parameters as one stochastic growing season for each projection period. These data included radiation, maximum and minimum air temperature and precipitation for four projection time (1982–2012 (baseline), 2015–2045, 2046–2075 and 2076–2105). LARS-WG is a stochastic weather generator based on the time series approach (Semenov and Stratonovitch, 2010). LARS-WG produces synthetic daily time series of solar radiation, maximum and minimum temperature and precipitation. LARS-WG applies observed daily weather data for a given site to compute a set of parameters for probability distributions of weather variables as well as correlations between them (Semenov and Brooks, 1999).

2.3. Weather generator uncertainty

Climate model uncertainty analysis was performed by two methods. First of all, uncertainty of solar radiation, maximum and minimum temperatures and precipitation has been evaluated by comparison between mean observed values and simulation results assuming normal distributions of the variables (Khan et al., 2006). In addition, uncertainty was evaluated by Wilcoxon rank sum method. This test is a nonparametric alternative to the two-sample *t*-test which is based solely on the order in which the observations from the two samples fall (Conover, 1980). Based on the Wilcoxon rank sum method, if the *P*-value is more than 0.05, there is no significant differences between populations and vice versa.

2.4. Potato growth model

The SUBSTOR-Potato model was used for simulating the baseline and future yield and growth characteristics of potato. This is one of sixteen models embedded within the DSSAT (v4.5) program (Jones et al., 2003). The SUBSTOR-Potato model was completely described by Griffin et al. (1993). The SUBSTOR-Potato model simulates on a daily basis the growth and development of the potato crop using information on climate, soil, management and cultivar. The model is divided into four main sub models simulating simultaneously the phenological development, the biomass formation and partitioning, soil water and nitrogen balances to provide a realistic description of the plant–soil–atmosphere system (Ritchie et al., 1995; Jones et al., 2003). The SUBSTOR-Potato model has been used more recently for climate change impact assessments (Holden et al., 2003; Daccache et al., 2011; Arora et al., 2013; Martre et al., 2017; Raymundo et al., 2017). Weather and soil data, agronomic practices and genetic coefficients of potato are the main inputs to run the SUBSTOR-Potato model.

2.4.1. Crop model calibration

It is important that the crop model can accurately predict observed variations in historical yield, before modelling climate impacts on future yield. For calibration and validation the SUBSTOR-Potato model, an experiment was performed in three years (2011, 2012 and 2013), that two years data were used for calibrating and one year for validating the model. So, the SUBSTOR-Potato was calibrated by two years experiment as spilt-plot based on the randomized complete block design with three replications, which was conducted in 2011 and repeated

in 2012. The treatments were three levels of planting dates (30 April, 15 May and 31 May) assigned to main plot, and three potato varieties (Arinda (early maturing), Sante (medium maturing) and Agria (delayed maturing)) as sub-plot. Agria is the most commonly planted potato variety in the region. The common planting date of the variety in the study area is about mid-May. Tubers class E (35–55 mm diameter) was used for the three cultivars planting. Soil of the experimental field in the 0–30 cm depth was silty loam with pH 7.49, containing total N (0.083%), total P (18.4 ppm), and total K (392 ppm) with an EC of 2.88 ds m^{-1}. In this experiment, the effects of planting dates on yield and morphological traits of three potato cultivars were investigated. Based on the soil analysis, 340 kg urea ha^{-1}, 190 kg triple superphosphate ha^{-1} and 85 kg potassium sulfate ha^{-1} was used. As soon as the tubers were sown irrigation was done, and was averagely continued every 10 days. During growth season, hand weeding was conducted three times. Some of the measured variables such as tuber yield, maximum leaf area index (LAI) in different growth stages, biomass, plant height, days to tuber initiation (DTTI), and days to harvest (DTH) were provided for the model as observed data. LAI was measured weekly using the LAI-2000 instrument (Li-Cor Inc, Lincoln, NE, USA). Crop management data including information about planting, emergence and harvest dates as well as nitrogen, potassium and phosphorus fertilizers applied levels was also collected. Finally, tillage practices and previous crop were set into the simulation. SUBSTOR-Potato model estimates tuber yield using five genetic coefficients differ by variety. Accurate simulation of tuber yield requires the correct genetic coefficients. Genetic coefficients were derived mainly from literature sources (Vermeer, 1990; Stastna et al., 2010) and experimental data (at GenCalc section of DSSAT software) under stress-free environment. The crop genetic input parameters used for studied potato cultivars are given in Table 1. Pooled observed data were used to calibrate the model for projecting the tuber yield, DTTI, LAI and DTH. For simulation of CO_2 effect on potato, the suggested values of CO_2 was add for mentioned scenarios in the weather file of DSSAT software based on IPCC (2000) report, and the CO_2 was simulated as “read from weather file”. The CO_2 concentration for baseline was considered as “default value (380 ppm)”. Other agronomic operations such as fertilizer rates were considered as baseline for all the periods, GCMs and scenarios.

2.4.2. Crop model validation

As mentioned, experimental data in 2013 year was used for validating the model. Nine pairs of data were used to compare difference between observed and simulated data. These data were measured and simulated variables for three varieties (Arinda, Sante and Agria) under three planting dates (30 April, 15 May and 31 May). Several criteria were used to quantify the difference between simulated and observed data. The normalized root mean-squared error (nRMSE) was computed to measure the deviation between measured and simulated values (Eq. (1)) (Loague and Green, 1991), while mean deviation (RMD) was calculated to evaluate systematic bias of the model (Eq. (2)). Model efficiency (ME) was calculated to estimate model performance in relation to the observed mean (Eq. (3)) (Nash and Sutcliffe, 1970). Moreover, linear regression was applied between simulations results and observations to evaluate model performance and correlation coefficient (R^2) for each simulation.

$$\mathrm{nRMSE} = \frac{100}{\bar{O}}\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{1}$$

$$\mathrm{RMD} = \frac{100}{\bar{O}}\sum_{i=1}^{n}\frac{P_i - O_i}{n} \tag{2}$$

$$\mathrm{ME} = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{3}$$

Where, P and O are simulated and observed data, respectively, $\bar{o}$ is the mean of observed data and n is the number of observations. The nRMSE illustrated the model's prediction error by heavily weighting high errors, whilst the RMD uses same weights for all errors, which tends to smooth out discrepancies between simulated and observed data. ME indicates the efficiency of the model by ranging from $-\infty$ to 1. The closer the model efficiency is to 1, the more accurate the model is. Another method for testing the difference between simulated and observed data was 1:1 line.

Table 1
Genetic coefficients for potato varieties during calibration of the DSSAT model.

Variety	G2	G3	PD	P2	TC
Arinda	2000	25.0	1.0	0.4	15
Sante	2000	22.5	0.9	0.6	15
Agria	2000	22.5	0.8	0.8	13

G2, leaf area expansion rate after tuber initiation ($cm^2\ m^{-2}\ d$); G3, potential tuber growth rate ($g\ m^{-2}\ d$); PD, index that suppresses tuber growth during the period that immediately follows tuber induction, P2, tuber initiation sensitivity to long photoperiods; TC, upper critical temperature for tuber initiation (°C).

2.5. Adaptation options

2.5.1. Planting date

Three planting dates, 30 April, 15 May (common planting date in the studied area) and 31 May were used to determine the best planting date under future climate change. As anthesis and tuber initiation stages which occurred simultaneously are the most sensitive potato growth stage, the mentioned planting dates were designed to assess the relationship between the maximum temperature in the study area and tuber initiation stage of potato.

2.5.2. Variety

Three diverse varieties of potato were selected for testing the adverse effects of climate change on potato. These varieties were included long season variety (Agria), medium season variety (Sante) and short season variety (Arinda). Agria is one of the most common cultivated varieties in Iran. This cultivar has high yield potential in comparison with other commercial cultivars.

3. Results and discussion

3.1. Climate uncertainty

The absolute errors of the downscaling model (absolute differences between observed mean of daily climatic data and climate projections) in the approximation of mean daily precipitation, solar radiation, daily maximum and minimum temperatures for each month was tested at 95% confidence level using non-parametric Wilcoxon rank-sum test that are shown in Fig. 1. Generally, model error was significantly higher for precipitation simulation compared to other climate parameters (Fig. 1). Simulation of precipitation showed the highest model error was observed during July, August and November, while June and October had the lowest values. September, December and March had the maximum values of model error for maximum temperature, minimum temperature and solar radiation, respectively. On the other hand, the reported p-values of the Wilcoxon rank sum tests for the differences of means of observed and downscaled data for all months are given in Table 2. The LARS model errors are found significant in the month of June and July in precipitation parameter, while for other months and climatic parameters, the LARS model errors are found insignificant at 5% significance level (Table 2). The results authenticate the acceptable ability of LARS for the region climate simulation.

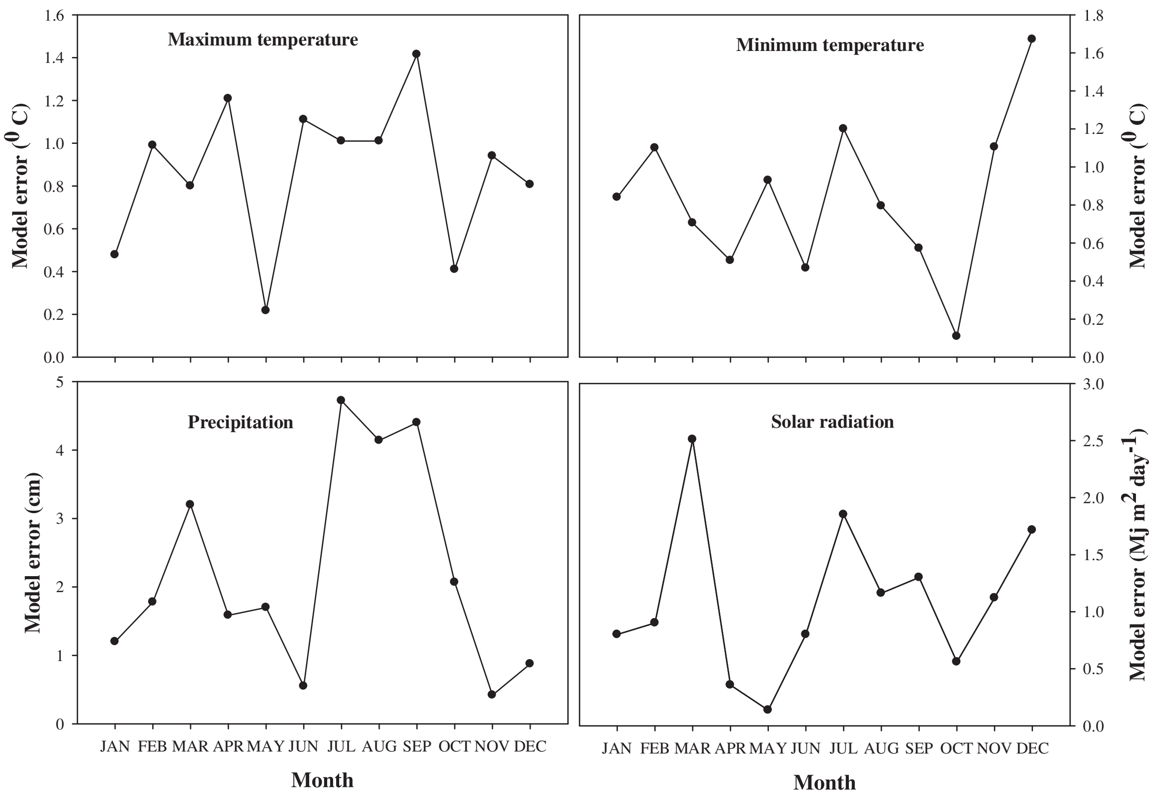

Fig 1. Model errors (absolute values) in downscaled daily climatic parameters.

Table 2
Test results (*p*-values) of the Wilcoxon rank sum test for the difference of means of observed and downscaled daily maximum and minimum temperature and precipitation at 95% confidence level.

Month	Minimum temperature	Maximum temperature	Precipitation	Solar radiation
JAN	0.632	0.211	0.157	0.200
FEB	0.271	0.124	0.203	0.923
MAR	0.115	0.691	0.381	0.127
APR	0.254	0.520	0.303	0.369
MAY	0.621	0.108	0.107	0.211
JUN	0.124	0.077	0.028	0.754
JUL	0.057	0.085	0.007	0.112
AUG	0.098	0.218	0.340	0.066
SEP	0.321	0.352	0.607	0.587
OCT	0.411	0.542	0.305	0.189
NOV	0.091	0.369	0.221	0.099
DEC	0.101	0.084	0.411	0.587

p-values show the significantly levels, so *p*-values ≤ 0.01, $0.01 <$ p-values ≤ 0.05 and *p*-values > 0.05 indicate significantly at 1%, 5% and non-significant, respectively.

3.2. Crop model validation

The evaluation of the SUBSTOR-Potato model showed adequate accuracy for simulating tuber yield, LAI, DTTI and DTH for potato (Table 3). The results showed that the normalized RMSE was low for all the parameters. The best nRMSE value (2.18%) was obtained for tuber yield, and DTH had the highest value of nRMSE (8.38%). In other words, the simulated values and observations for these parameters generally matched well and differences were less than 10% based on the nRMSE values. The nRMSE value lies within the range of other potato modeling studies. Simulations by Kleinwechter et al. (2016), Travasso et al. (1996), Ritchie et al. (1995) and Raymundo et al. (2017) with SUBSTOR-potato show nRMSE of 28.1%, 14.7%, 44.9% and 21.4%, respectively. The simulated tuber yield for our study has a relatively small model error when compared to previous studies. According to the values of ME and RMD, the model accurately predicted all of the studied parameters (Table 3). The coefficient of determination (R^2) between the simulated and observed tuber yield was 0.97 and the values of this parameter were 0.79, 0.86 and 0.94 for LAI, DTTI and DTH, respectively with a slope of the regression equation that was not statistically different from one (Fig. 2). Raymundo et al. (2017) illustrated that the SUBSTOR-potato model was shown to be suitable to simulate tuber growth and yields over a wide range of current growing conditions and crop management practices across many geographic regions.

Table 3
Comparison of simulated and observed parameters of potato by Root Mean-squared Error (nRMSE), Model Efficiency (ME) and Root Mean Deviation (RMD).

Parameters	nRMSE	ME	RMD
Fresh tuber yield	2.18	0.61	2.18
LAI	8.12	0.82	4.21
DTTI	6.12	0.72	1.18
DTH	8.38	0.81	0.58

LAI: Leaf area index, DTTI: Day to tuber initiation and DTH: Day to harvest.

3.3. Potato responses to future climate change for common variety (Agria)

3.3.1. Maximum leaf area index

Simulation results indicated that leaf area index (LAI) of potato will be affected by climate change and in all evaluated scenarios, it will be reduced compared with the baseline (1988–2012) (Table 4). In the future years, in all scenarios and both general circulation models (G-CMs), maximum LAI will be diminished which was lower in B1 scenario than the other two scenarios in both IPCM4 and HadCM3 models (Table 4). The highest drop in max LAI was found under A2 scenario in 2090, which will be 24.78% and 27.52% in HadCM3 and IPCM4 GCMs, respectively and compared with baseline years. The lowest drop will be belonged to the B1 scenario in 2030, which the reduction values are

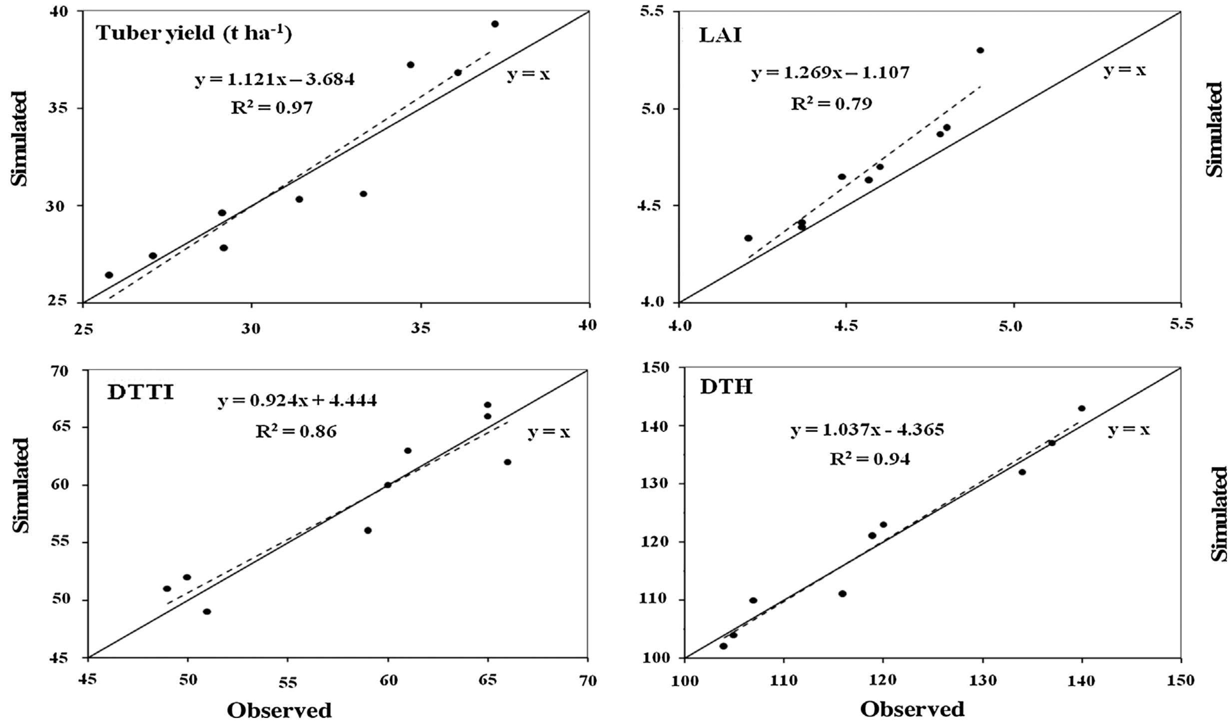

Fig. 2. Comparison of simulated and observed fresh tuber yield, leaf area index (LAI), day to tuber initiation (DTTI) and day to harvest (DTH).

estimated to be 10.05% in HadCM3 and 11.34% in IPCM4 GCMs (Table 4). Among with the scenarios in HadCM3, A2 scenario will have a lower max LAI in comparison with B1 and A1B and so the reduction of max LAI in this scenario will be higher than the others (Table 4). Results of the simulation in IPCM4 model are similar to the simulated results of HadCM3 model (Table 4). In general and according to the results, it could be implied that in IPCM4, potato plant will have a lower max LAI under different scenarios and during the years, compared with HadCM3 model. This fact shows that climate change severity and its negative effects on potato growth and development is more dominant in IPCM4 than HadCM3 general circulation model.

3.3.2. *Phenology*

In both GCMs and during the simulated years and under different scenarios of climate change, number of days from planting to tuber initiation stages of potato will be decreased compared with the current condition of Fereydoon-Shahr region (Table 4). A1 B (58 days) and A2 (59 days) scenarios of HadCM3 will have the fewest day number to tuber initiation in 2090. Based on these scenarios, days to tuber initiation would be diminished by 10.77% and 9.23% in 2090 than the baseline years for HadCM3 (Table 4). In IPCM4 model, the lowest day to tuber initiation index was simulated for A2 scenario in 2060 and 2090 by 58 and 57 days, which shows a reduction of 12.31% and 10.77%, respectively and compared with the current condition (Table 4). It seems that the elevation of air temperature by 1–5 °C based

Table 4
Simulated some studied traits of potato with HadCM3 and IPCM4 under A1B, A2 and B1 scenarios in 3 periods.

GCM Model	Scenario	Year	Maximum LAI	DTTI (day)	DTH (day)	Fresh tuber yield (t ha^{-1})
		Baseline	4.57	65	137	29.15
HadCM3	A1B	2030	3.87 (15.35)[a]	62 (4.62)	133 (2.92)	24.18 (17.05)
		2060	3.76 (17.63)	60 (7.69)	129 (5.48)	23.44 (19.58)
		2090	3.74 (18.26)	59 (9.23)	127 (7.30)	23.23 (20.29)
	A2	2030	3.76 (17.46)	60 (7.69)	129 (5.48)	23.44 (19.60)
		2060	3.64 (20.46)	60 (7.69)	129 (5.48)	22.52 (22.73)
		2090	3.44 (24.78)	58 (10.77)	125 (8.76)	21.13 (27.53)
	B1	2030	4.11 (10.09)	60 (7.69)	129 (5.48)	25.88 (11.21)
		2060	4.03 (11.81)	61 (6.15)	131 (4.38)	25.32(13.13)
		2090	3.91 (14.43)	61 (6.15)	131 (4.38)	24.48 (16.04)
IPCM4	A1B	2030	3.79 (17.10)	62 (4.62)	133 (2.92)	23.61 (19.00)
		2060	3.75 (17.94)	59 (9.23)	127 (7.30)	23.34 (19.93)
		2090	3.71 (18.79)	59 (9.23)	127 (7.30)	23.06 (20.88)
	A2	2030	3.73 (18.39)	60 (7.69)	129 (5.48)	23.19 (20.43)
		2060	3.57 (21.81)	58 (10.77)	125 (8.76)	22.09 (24.23)
		2090	3.31 (27.52)	57 (12.31)	123 (10.2)	20.24 (30.58)
	B1	2030	4.05 (11.34)	63 (3.08)	135 (1.46)	25.48 (12.60)
		2060	3.95 (13.53)	62 (4.62)	133 (2.92)	24.77 (15.03)
		2090	3.83 (16.11)	61 (6.15)	131 (4.38)	23.93 (17.90)

LAI: Leaf area index, DTTI: Day to tuber initiation and DTH: Day to harvest.
[a] The number in parentheses indicates the decrease percentage compared to baseline value.

on the mentioned scenarios (IPCC, 2007) is the main reason of this trend. Although some other nutritional or environmental parameters could affect harvested yield, but since the mentioned parameters was almost under control and their possible effects was minimized during the experiment, the temperature is the most effective factor here and could explain the trend. Kleinwechter et al. (2016) suggested that temperature is a more critical factor where potato is grown during summer. Enhanced temperature will speed up the plant growth and causes to accelerate flowering and ripening. Thus, reduction of growth season as a result of climate change and global warming is expected (Daccache et al., 2011; Eyshi Rezaei et al., 2015). Declining of growth period will probably decrease potato yield because the available time for utilization of production resources will be reduced. Decreasing anthesis stage in maize under future climate change condition was also reported by Moradi et al., (2013, 2014).

Modeled values of day to tuber initiation in all the scenarios and models (except B1 scenario in HadCM3 model) showed that along with the time, this index was reduced, which 2090 year will have a lower index than 2060 and 2030 (Table 4). In both GCMs, the highest and lowest reduction in vegetative growth stage period were observed on A2 and B1 scenarios, respectively. Considering the fact that this reduction will probably diminished the yield, it seems that the lowest and the highest potato yield will be achieved in the mentioned scenarios, respectively. Meza et al. (2008) reported that elevated temperature resulted in accelerating of phenologic stages and development trend of maize. It was also demonstrated that under climate change simulation and in all scenarios, growth degree day (GDD) needed for completing plant growth and development was provided in a shorter period of time.

Under all scenarios and GCMs, days number from planting to harvest will be declined compared with current condition (Table 4). This reduction is variable from 2.92% to 8.76% in HadCM3 and from 1.46% to 10.22% in IPCM4GCMs. The substantial decrease in both GCMs was observed under A2 scenario in 2090, with the values of 8.76% for HadCM3 and 10.22% for IPCM4 models (Table 4). Between the scenarios, potato will have a longer growth period under B1 scenario, although this value is also less than the value of baseline (1988–2012). Higher amounts of day to harvest in B1 scenario compared with A1 B and A2 scenario could be related to the less increase of air temperature under climate change condition in this scenario (IPCC, 2007), which simulated climatic data by LARS-WG model support this event. As it was previously mentioned, enhanced temperature will accelerate growth and development stages and reduce maturity period in plants, consequently (Parry et al., 1999; Parry et al., 2004), which may also diminished potato yield. Decreased growth period under future climate change condition was also evaluated and reported in maize (Jones and Thornton, 2003; Moradi et al., 2013, 2014), soybean (Mall et al., 2004), wheat (Lawlor and Mitchell, 2000; Remy et al., 2003; Van Oijen and Ewert, 1999) and rice (Prasad et al., 2006). Comparing the two GCMs was also indicated that in IPCM4, maturing period was shorter than HadCM3 in all scenarios and years (Table 4).

3.3.3. Fresh tuber yield

The results indicated that tuber yield of common variety of potato under all scenarios (A1B, A2 and B1) in both GCMs and during the evaluated years will be declined in comparison with the current condition in Fereydoon-shahr region (Table 4). The reduction will be variable from 11.21% to 27.53%for HadCM3 model and from 12.60% to 30.58%for IPCM4model. In HadCM3 GCM, B1 scenario in 2030 had the least difference with the baseline years (29.15 t ha^{-1}), which is about 11.21% lower than the current condition (Table 4). In IPCM4 model, the highest tuber yield was simulated under B1 scenario in 2030 (25.48 t ha^{-1}), which is a reduction of about 12.60% compared with the baseline year (Table 4). Climate change effects on tuber yield of potato were also simulated for 2055 and 2075 years and decreasing trend under climate change condition was reported (Holden et al., 2003). They used HadCM3 for their assessments and made their simulations based on a 1.6 °C enhancement of air temperature. Hijmans (2003) reported that global potential potato yield decreases by 18% to 32% as affected by climate change.

The considerable point which needs to take into account in evaluation of climate change effects on crops yield is enhancement of CO_2. In fact, in the researches which this parameter was considered, different results were reported. For instance, Daccache et al. (2011) in the evaluation of climate change effects until 2050 on potato yield in UK reported that tuber yield in different regions of UK will increase from 2.9% to 6.2% compared with the baseline years. They considered CO_2 concentration for A1F and B1 scenario as 593 and 489 ppm in HadCM3 model, while CO_2 concentration in baseline conditions was considered as 330 ppm. In this study CO_2 concentration was considered as 380 ppm for baseline. It seems that choosing the higher CO_2 concentration (380 ppm) in this study than the mentioned studies (330 ppm) for baseline led to that CO_2 elevated in future climate change had no significant effect on potato tuber yield. In other words, negative impact of temperature on the fresh tuber yield was higher than positive effect of CO_2 enrichment.

A2 scenario in both GCMs showed the lowest tuber yield in 2090 (21.13 t ha^{-1} for HadCM3 and 20.24 t ha^{-1} for IPCM4) which means a drop of 27.53% and 30.58% in tuber yield compared with the baseline conditions (Table 4). Generally, B1 scenario in HadCM3 and IPCM4 GCMs showed the minimum decline in tuber yield in comparison with the baseline and A2 scenario simulated the highest reduction of tuber yield (Table 4). Results also indicated that this decreasing trend will continue in the future, which means the lowest yield will be observed in 2090, based on the all scenarios. In fact, in A1B, A2 and B1 scenario, a decline of 20.29%, 27.53% and 16.04% in tuber yield for HadCM3 model and a reduction of 20.88%, 30.58% and 17.90%for IPCM4 model was simulated, respectively.

Tuber yield reduction under different scenarios of climate change in Fereydoon-Shahr region could be considered as a result of elevated air temperature, as the results of climatic data simulation in this region showed that in both GCMs, temperature will be enhanced along the time. This trend will harmfully affect tuber yield through the effects on growth and development stages and plant photosynthesis. Besides reducing growth period, enhanced temperature will also raise respiration process and so decreasing photosynthesis outputs and tuber yield. As the results of climatic data simulation indicated, B1 scenario in both GCMs will probably show a smaller increase in air temperature in comparison with the other two scenarios. Thus, the reduction of tuber yield will be less considerable because of the longer growth period available for resources utilization, and moreover, the elevation of respiration process due to the enhanced temperature will be less significant. Resop et al. (2016) indicated that potato yields declined by an average of 50% as affected by climate change. Mera et al. (2006) demonstrated that the maximum effect of enhanced temperature is on anthesis stage and reduces the yield by decreasing period and percentage of fertilization. They also declared that an increase of 2 °C in air temperature caused to reduce anthesis period from 10 to 8 days in maize with a substantial effect on produced grains and final yield. Available scientific evidences suggest that declining of grain-filling period due to the elevated temperature is the most substantial parameter in reducing crops yield under climate change conditions (Asseng et al., 2004; Challinor et al., 2007). On the other hand, Meza et al. (2008) implied that the most important effect of climate change is on photosynthesis process and so on the produced yield. Reducing growth period as a very effective factor in decreasing crops yield in the future was also demonstrated by Alexandrov and Hoogenboom (2000). Based on the results of this experiment, it seems that enhanced temperature will harmfully affect growth season, photosynthesis rate, anthesis and tuber initiation and so reducing tuber yield between 11.21% to 30.58% under different scenarios and GCMs (Table 4). Kleinwechter et al. (2016) indicated that higher temperatures do not only affect tuber initiation. Heat also affects different components of crop growth, such as

Table 5
Simulated potato fresh tuber yield (t ha^{-1}) for various planting dates and varieties with HadCM3 and IPCM4 under A1B, A2 and B1 scenarios in 3 periods.

GCM Model	Scenario	Year	Arinda (Early maturity)			Sante (Medium maturity)			Agria (Common and delayed maturity)		
			Early PD	Common PD	Delayed PD	Early PD	Common PD	Delayed PD	Early PD	Common PD	Delayed PD
		Baseline	36.10	34.70	37.20	31.40	29.20	33.30	28.02	29.15	31.82
HadCM3	A1B	2030	32.84	28.27	34.40	27.91	24.38	30.41	22.83	24.18	27.24
		2060	31.93	27.39	33.46	27.11	23.64	29.57	22.17	23.44	25.73
		2090	31.67	27.15	33.20	26.89	23.43	29.33	21.99	23.23	25.54
	A2	2030	31.92	27.39	33.45	27.11	23.63	29.56	23.17	23.44	25.73
		2060	30.79	26.30	32.29	26.12	22.72	28.52	21.36	22.52	24.88
		2090	29.06	24.64	33.20	24.62	21.32	27.56	20.12	21.13	24.12
	B1	2030	34.95	30.30	36.58	29.74	26.08	32.36	24.34	25.88	28.00
		2060	34.26	29.64	35.86	29.14	25.52	32.71	23.84	25.32	27.48
		2090	33.21	28.63	34.78	28.23	24.67	30.75	23.09	24.48	26.69
IPCM4	A1B	2030	32.14	27.60	33.68	27.30	23.81	29.76	22.32	23.61	25.89
		2060	31.80	27.27	33.33	27.00	23.53	29.45	22.08	23.34	25.64
		2090	31.46	26.95	32.98	26.71	23.26	29.14	21.84	23.06	25.38
	A2	2030	31.62	27.10	32.14	24.85	23.39	29.29	21.95	23.19	25.50
		2060	30.25	25.78	31.73	25.65	22.28	28.02	20.98	22.09	24.47
		2090	28.34	23.58	30.39	23.66	20.43	26.49	19.34	20.24	23.50
	B1	2030	34.45	29.82	36.06	29.31	25.68	31.90	23.98	25.48	27.62
		2060	33.57	28.97	35.15	28.54	24.97	31.08	23.35	24.77	26.96
		2090	32.54	27.98	34.09	27.64	24.13	30.13	22.61	23.93	26.19

PD: planting date.

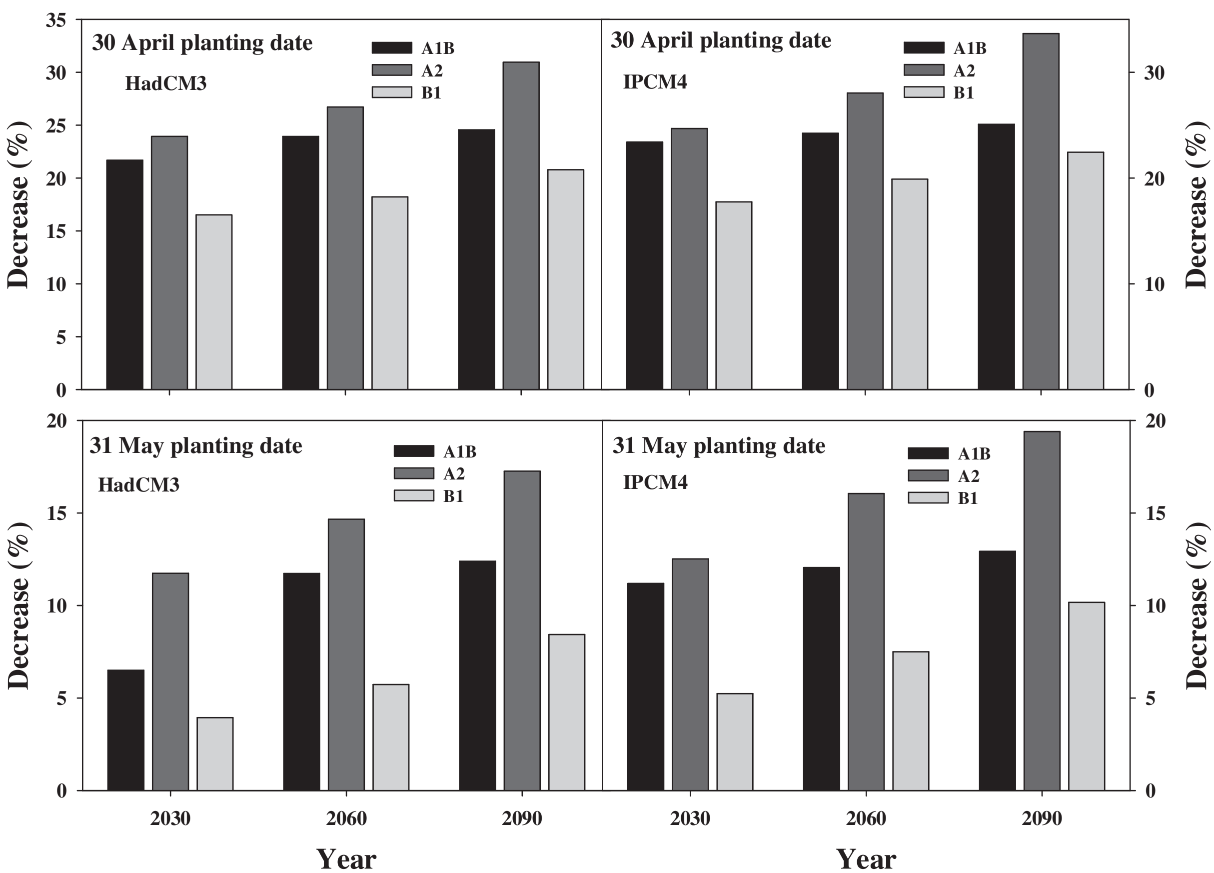

Fig. 3. Decrease percentage of simulated potato fresh tuber yield in early planting date (30 April) and delayed planting date (31 May) using HadCM3 and IPCM4 models under A1B, A2 and B1 scenarios for 3 periods rather than common planting date (15 May) in baseline.

photosynthesis, vegetative growth, and tuber bulking.

3.4. Adaptation strategies

3.4.1. Changing the planting date

One of the most important agronomical approaches in adaptation strategies to climate change condition is changing the planting date. It was found in various researches that changing planting date is one of the simplest and most low cost adaptation strategies (Ludwig and Asseng 2006; Smit et al., 2000). So in this experiment, changing planting date in the forms of early and delayed planting (compared with the conventional planting date) was simulated to evaluate its

effects on growth and yield of potato.

Simulation results indicated that delayed planting (31 May) alleviated the harmful effects of climate change by improving tuber yield. The maximum elevation compared with the conventional planting (15 May) was simulated under A2 scenario in IPCM4 model and in 2090 by 16.11% (Table 5). In HadCM3 model and under A2 scenario in 2090, delayed planting will have the highest increase in yield by the value of 14.17% (Table 5). Early planting (30 April) in both GCMs and under all scenarios reduced tuber yield (5% on average) compared with conventional planting date (Table 5). It was previously reported that changing planting date could be used as an adaptation strategy to climate change conditions. Simulation results in rice showed that early planting enhanced the yield between 20%-27% than conventional planting date (Challinor et al., 2007). Yield improving effect of early planting date under future climate change conditions was also demonstrated by Moradi et al. (2013).

The lowest tuber yield was simulated in early planting in IPCM4 model under A2 scenario and in 2090 (19.34 t ha^{-1}) and the highest was simulated in delayed planting in HadCM3 model under B1 scenario in 2030 (28 t ha^{-1}) (Table 5). Along the time and in all planting dates under all scenarios, tuber yield will be declined and the lowest value was anticipated in 2090. Between the scenarios, B1 and A2 have the highest and the lowest tuber yield, respectively. A1 B is an intermediate scenario with values of tuber yield more than A2 and less than B1 scenario (Table 5). It was shown that A2 scenario has the most negative effects on yield and B1 has the least negative role (Moradi et al., 2014). They also reported the reduction of yield along the time under future climate change conditions.

It was also observed that in HadCM3model, early planting in 2030 will show the lowest reduction in yield, compared with 2060 and 2090 (Fig. 3). Obtained results for IPCM4 model was similar to the results of HadCM3 model. In both GCMs, the maximum decrease of yield in early planting (30 April) compared with conventional planting date (15 May) in baseline year was simulated under A2 scenario and in 2090 (30.96% and 33.66% for HadCM3 and IPCM4 GCMs, respectively). The minimum reduction of yield is also simulated under B1 scenario in 2030 for both GCMs as 16.52% and 17.75% for HadCM3 and IPCM4 models, respectively (Fig. 3).

According to the simulations and under future climate change conditions, tuber yield in delayed planting (31 May) will be declined compared with the conventional planting date (15 May) during the baseline. The most significant decrease was observed in A2 scenario and the least was observed in B1 scenario (Fig. 3). Along the time, the amount of reduction in delayed planting date will be more considerable in comparison with the conventional planting in baseline, as in both GCMs and under all scenarios, 2090 will show the most substantial decline in tuber yield (Fig. 3). The least decrease of yield in delayed planting is anticipated in HadCM3 model under B1 scenario in 2030 by the value of 3.94% (Fig. 3) and the highest reduction is anticipated in IPCM4 model and under A2 scenario in 2090 by the value of 19.40%. Based on the achieved results, it could be implied that delayed planting of potato is a more appropriate approach than conventional and early planting in order to mitigating the harmful effects of climate change in the assessed region. It is also necessary to consider that regards to the increasing trend of air temperature in the future, reduction of potato yield is expected. Hence, agronomical management tools including changing of planting date (as it was simulated in this research) could be applied as a proper and cost-effective approach in adopting of potato to the future climate change conditions.

As it was shown in Fig. 4, in conventional planting date (15 May), tuber initiation stage of potato (65 days after planting)coinciding with the maximum air temperature during the growth season. Since anthesis and tuber initiation are known as the most sensitive stages to heat and high temperatures and considering the fact that anthesis and tuber initiation stages in potato are almost simultaneously, adaptation strategies should be managed in order to avoid the exposure of these stages to high temperatures. Thus, it seems that delayed planting will alleviate the harmful effects of heat during tuber initiation stage and will show an enhanced yield compared with the other planting dates in the future. In this regard, simulation results of early planting mostly showed a reduction in yield, because more days of tuber initiation stage are coincided with high temperatures of the region. The problem which generally happens in delayed planting of potato is exposure to chilling condition of early autumn. But Southworth et al. (2000) reported that with respect to the global warming and relative elevation of air temperature in early autumn under future climate change conditions, delayed planting will not face with the chilling danger of last season. Hence and as it was mentioned, this approach is still appropriate and applicable.

3.4.2. Using various varieties

One of the other approaches to confront the negative effects of climate change is applying various varieties, considering that they will show different responses to climate change conditions because of different growth properties including the duration of phonologic stages or different resistance to elevated temperatures. Comparing early maturing, medium maturing and late maturing varieties in climate change researches and choosing varieties with higher adoptability is a very efficient way among the adaptation strategies.

The results showed that tuber yield of all varieties (Arinda as the early maturing verity, Sante as the medium maturing variety and Agria as the late maturing variety) will be declined in both GCMs and under all scenarios and during three evaluated periods and in all three planting dates. Harmful effects of climate change (elevated temperature) on tuber yield of the varieties showed an increasing trend, which the lowest yield for all three varieties was simulated in 2090 for all GCMs and scenarios and planting dates (Table 5). Reducing the duration of phonologic stages and tuber yield compared with the conventional conditions was more considerable in A2 scenario A1 B and B1 scenarios (Table 5). This result is in a context with the report of Intergovernmental Panel on Climate Change (IPCC, 2007), which the mean elevation of air temperature until 2100 in A2 scenario (2–5.4 °C) was anticipated more than A1 B (1.7-4.4 °C) and B1 (1.1-2.9 °C) scenarios. Increased temperature will accelerate the development rate and declining total growth duration. This reduction limits the available time for filling the economical part of plant and so reduces the yield compared with the current values (Abraha and Savage 2006). Meza et al. (2008) also demonstrated that climate change will compel plants to finalize their growth in a shorter period of time and this will resulted in 10% to 30% reduction in yield in the future. Although there are some reports implied the enhancement of tuber yield of potato under climate change conditions (Wolf and Van Oijen, 2003; Peiris et al., 1996). Wolf and van Oijen (2003) was simulated the elevation of tuber yield in potato for 2050 in the most parts of Europe.

Sante and Arinda varieties showed a higher yield in all scenarios and in comparison with the conventional variety (Agria), which was more considerable in Arinda (a new and early maturing variety) (Table 5). Early and delayed planting in both medium (Sante) and early (Arinda) maturing varieties is simulated to produce higher tuber yield compared with the conventional planting date and the maximum tuber yield in the mentioned varieties is belonged to the delayed planting (Table 5). The highest simulated yield was related to delayed planting (31th of May) of Arinda variety in HadCM3 model and under B1 scenario in 2030 with 36.58 t ha^{-1} tuber yield which shows a minor decline (about 1.7%) compared with the yield of this variety in the baseline years (37.20 t ha^{-1}). Agria had a lower TC (13) than Arinda and Sante varieties (15). Parameters TC (critical temperature) play a key role at anthesis and tuber initiation. If temperature is above TC, the tuber initiation and tuber bulking is reduced or inhibited (Raymundo et al., 2017). An increase in the parameter for TC may increase tuber yield in warm environments or help maintain stable yields when temperatures rise. The higher values of this parameter can be interpreted as

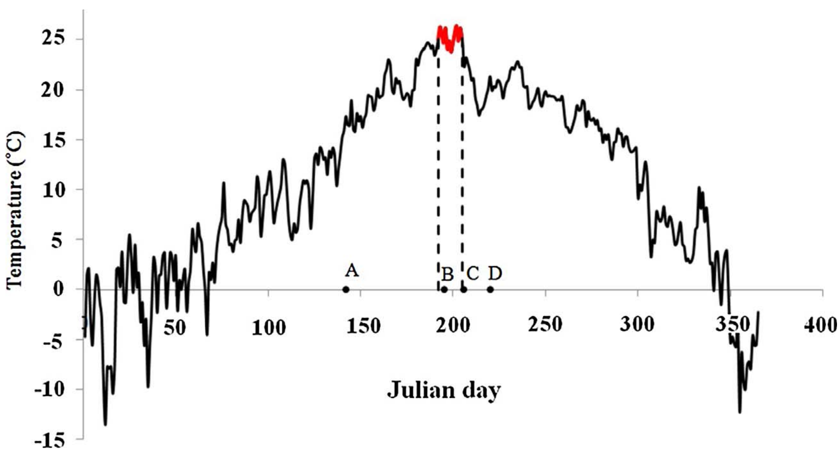

Fig. 4. Long-term mean temperature of Fereydoon-Shahr region. A, B, C, and D indicate the common planting time, tuber initiation time of early planting, tuber initiation time of common planting and tuber initiation time of delayed planting for common variety (Agria), respectively.

improved heat tolerance (Raymundo et al., 2017).

Since the peak of air temperature in Fereydoon-Shahr region is in the middle of July and this period of time is coincident with the tuber initiation stage of potato (Fig. 4), so it seems that cultivation of early maturing varieties may cause non-compliance of tuber initiation stage with the peak of air temperature which could alleviates harmful effect of climate change.

The most inappropriate planting date for Arinda variety under current and future conditions is 15 May (conventional planting date in the region), when the tuber initiation stage and peak of air temperature are coincident. This will cause more reduction of tuber yield under future climatic condition since the air temperature has an elevating trend (Fig. 5). So in Arinda variety early (30 April) and late (30 May) planting date show a better result than the conventional planting date because of the non-compliance of tuber initiation stage with the peak of air temperature. On the other hand and in the early planting system, given that the tuber initiation stage is happened earlier than the peak of air temperature and tubers are initiating at this time, so earlier planting is probably more affected by the heat of temperature and may produce lower yield compared with the late planting system.

For Sante variety, late planting is also the most suitable planting date, because tuber initiation stage and peak of air temperature in not happening simultaneously at all and this planting date will tolerate the least negative effect of climate change in the future (Fig. 5). While in the conventional planting date, the first days of tuber initiation is completely coincident with the peak of air temperature and in delayed

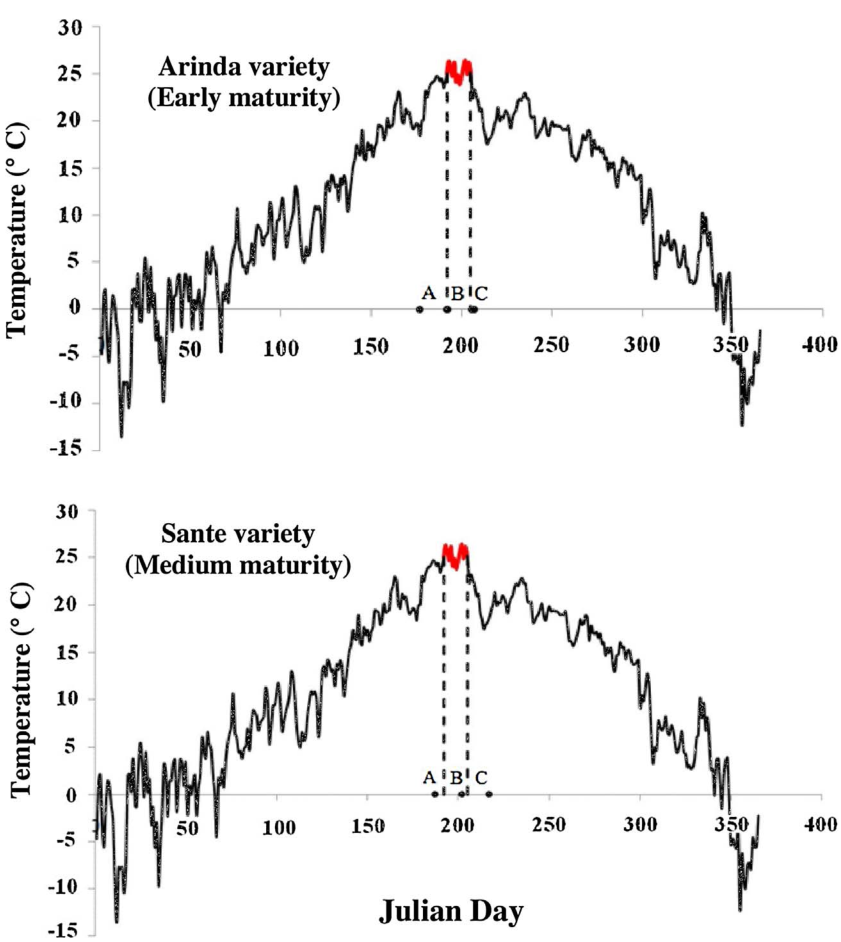

Fig. 5. Tuber initiation time of Arinda (early maturity) and Sante (medium maturity) varieties in Fereydoon-Shahr region. A, B, and C indicate the tuber initiation time of early planting, tuber initiation time of common planting and tuber initiation time of delayed planting, respectively.

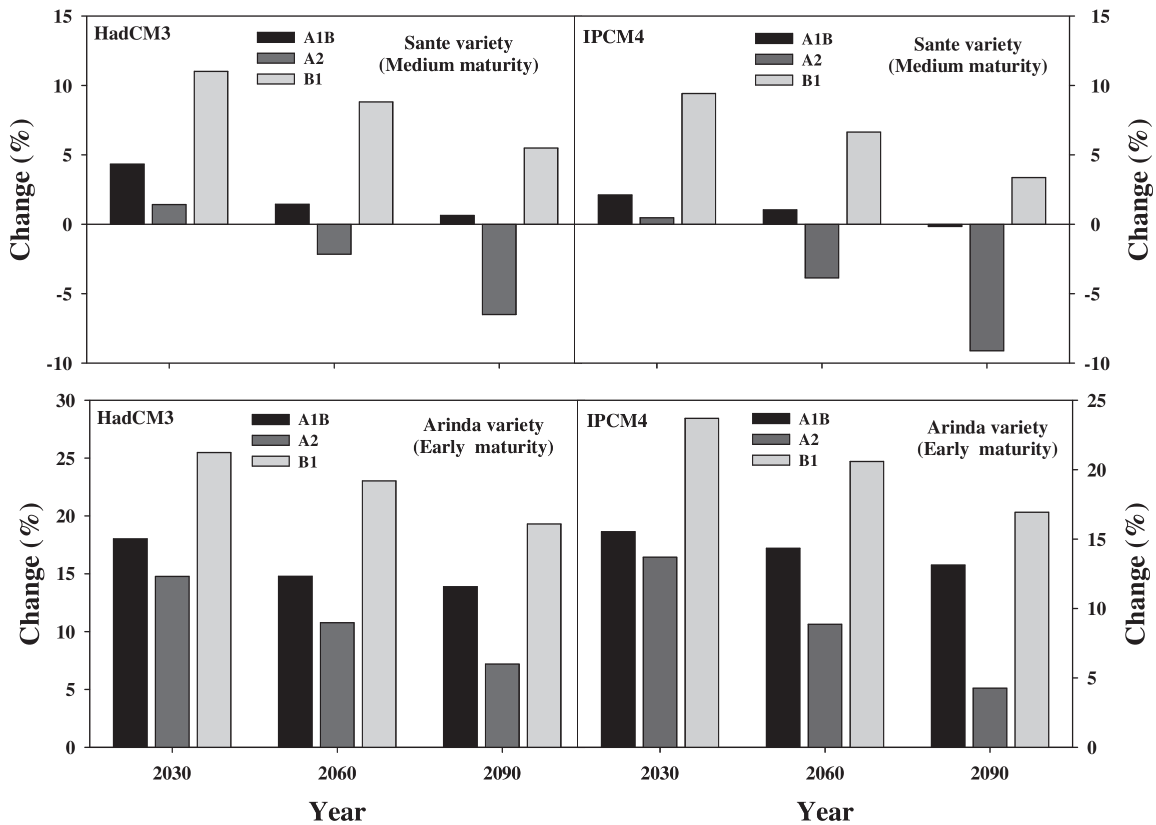

Fig. 6. Change percentage of simulated potato fresh tuber yield for Sante (medium maturity) and Arinda (early maturity) varieties in delayed planting date (31 May) using HadCM3 and IPCM4 models under A1 B A2 and B1 scenarios for 3 periods rather than common variety (Agria) and planting date (15 May) in baseline.

planting, the late part of tuber initiation is encountered with the heat (Fig. 5). Considering that the primary stages of anthesis and tuber developing of potato is more sensitive to heat stress than the late stages of anthesis, thus yield reduction of early planting is probably less than conventional planting date.

Based on these achievements, it could be implied that choosing appropriate varieties and planting dates is an efficient approach in order to adaptation of potato to the future climate change conditions. It was previously reported that anthesis and tuber initiation are the most sensitive stages of plants and using tolerant and adoptable varieties is introduced as a strategy for adaptation to high temperatures (Roy and Kumar Basu, 2009).

According to the simulation results of this experiment, the best planting date for both Sante and Arinda varieties under future climate change conditions was simulated in delayed planting system (31 May) (Table 5). Hence, the difference of yield values between these varieties with conventional variety and planting date (Agria in 15 May) was compared. Simulated yield change percentages for Sante variety was varied from −6.50% under A2 scenario in 2090–11.01% under B1 scenario in 2030 for HadCM3 model (Fig. 6). In IPCM4, the range was from −9.12% to 9.42% under A2 scenario in 2090 and under B1 scenario in 2030, respectively (Fig. 6).

Regards to Arinda variety in delayed planting, the highest and the lowest percentage of yield change compared with conventional variety and planting date in both GCMs were obtained under A2 scenario in 2090 and B1 scenario in 2030 (Fig. 6).

Whereas, the simulated results showed that the delayed planting date has the better advantage rather than other planting date for mitigating climate change impact on potato production, therefore, this planting date was examined for the Arinda and Sante varieties. Delayed planting of Sante variety in almost all cases resulted in improved tuber yield compared with conventional variety and planting date (Agria in 15 May) and it was just showed a reduction under A2 scenario in 2090 for HadCM3 model and in 2060 and 2090 for IPCM4 model (Fig. 6). While in Arinda variety, delayed planting under all evaluated scenarios and years and in both GCMs will enhance tuber yield in the region and future climate change conditions (Fig. 6).

To sum up, with respect to the non-compliance of tuber initiation stage with the peak of air temperature and high production potential of Arinda compared with the other varieties, selecting 31 May and Arinda as the planting date and variety is introduced as the most appropriate approach of agronomical management in the region in order to alleviate negative effects of climate change. Moradi et al. (2014) also simulated using varieties with the different growth period of maize to mitigate harmful effects of climate change and it was observed that choosing early maturing varieties with shorter growth period could be applied as an adaptation strategy under climate change conditions. Although these results were contradictory with the achievements of Tingem and Rivington (2009), as they reported that using late maturing varieties is more efficient than early maturing varieties.

4. Conclusion

Simulation results indicated that growth and development of potato will be affected by climate change under all evaluated scenarios and the yield will be decreased in comparison with the baseline years. The most substantial reduction of tuber yield was simulated under A2 scenario in 2090 for both HadCM3 and IPCM4 models. Planting date change and using various varieties were investigated as the adaptation approaches and it was anticipated that delayed planting (31 May) will enhance tuber yield under future climate change conditions. In contrary, early planting (30 April) will accelerate harmful effects of climate change. Delayed planting will cause the non-compliance of tuber initiation stage with the peak of air temperature and will mitigate negative effects of heat, while this non-compliance is not obtainable in early planting. In general, it could be implied that delayed planting is a more efficient

approach compared with conventional and early planting system to mitigate harmful effects of climate change.

Sante and Arinda varieties showed higher yields under all scenarios compared with Agria which is the conventional variety of the region. This dominance was more obvious in Arinda which is a new and early maturing variety than Sante variety. Tuber yield of delayed and early planting systems was higher than conventional planting in Arinda as a result of non-compliance of tuber initiation stage with the high temperatures. Thus, the most appropriate planting date for both Sante and Arinda varieties under future climate change conditions was simulated as delayed planting date (31 May). In general, Arinda variety and delayed planting system is reported as the most efficient agronomical approaches in order to mitigate harmful effects of climate change and it is proposed to be considered in designing and managing agricultural ecosystems of the region for future conditions. The limitation of the research was that the effects of technology improvement on potato production didn't consider for future due to lack of sufficient data. It is suggested that for future research can be considered irrigation and organic fertilizers application as other strategies. And also, it seems that running the more and newer models and scenarios is necessary.

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